

Anomalous Narrow-Line Quasars in the Sloan Digital Sky Survey

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ABSTRACT

We describe a new class of Type I quasars with narrow $H\beta$ broader than 1200 km/s, above the velocity believed possible for gas in the quasar narrow-line region. We identify this group of quasars as a distinct population because of a variety of spectral and photometric signatures common to these “anomalous narrow-line quasars” (ANLs) but atypical of other quasars. One prominent signature is suppression of the $[OIII]\lambda 4959, 5007$ emission-line, in many cases accompanied by broadening similar to the $H\beta$ line. We demonstrate that ANLs comprise at least 11% and most likely approximately one quarter of the SDSS Type I quasar population at $0.2 < z < 0.8$. The most striking feature of ANLs is a strong correlation between narrow $H\beta$ width and the width of the broad component of the $H\beta$ emission line. Another feature of ANLs is a diminished $[OII]$ line, which might indicate a connection between ANLs and the interstellar mediums of their host galaxies, through reduced photoionization or star formation. We find that it is difficult to produce ANLs using the current quasar standard model.

Key words: black hole physics — galaxies: evolution — galaxies: nuclei — quasars: general — accretion, accretion disks

1 INTRODUCTION

Although quasars are luminous enough to be detected at large distances, they are too small to be resolved into multiple spatial elements except at very short distances (e.g., Marconi et al. (2006)) or when lensed by a foreground object (Sluse et al. 2011). As a result, our best tool for mapping the region around the central supermassive black hole in higher-redshift active galactic nuclei has been spectroscopy. Each spectral line is associated with a specific ionization potential, and the shape of the line corresponds to the peculiar velocity profile of the emitting gas, complicated by parameters such as densities, abundances, temperatures, and effects of radiative transfer. There is a long history of studying quasar emission lines and their correlations (cf. Boroson & Green (1992)), much of which has helped to develop our standard model for Type I quasars (Sulentic et al. 2000; Gaskell 2009). In this paper, we describe a new class of quasars with distinct spectroscopic features that do not appear to fit easily into that standard model.

The standard picture built from existing data consists, from the black hole outward, of (cf. Peterson (2008)):

- The central black hole
- A hot accretion disk, beginning near the “innermost stable circular orbit” (ISCO), typically a few Schwarzschild

radii away with an exact radius dependent upon the spin of the central black hole. The accretion disk and corona are believed to emit the quasar continuum.

- The “broad-line region” (BLR), $\sim 0.1 - 1$ pc away, from which high-velocity gas produces correspondingly broad spectral emission lines, with typical FWHM in the 2000–20000 km/s range. Prominent emission lines visible in optical spectra at $z > 0.5$ include, from ionization potential placing them nearest to the central black hole, CIV, a broad component of $H\beta$, and MgII. In quasar virial mass estimators (McLure & Jarvis 2002; McLure & Dunlop 2004; Vestergaard & Peterson 2006; Wang et al. 2009; Onken & Kollmeier 2008; Risaliti et al. 2009; Rafiee & Hall 2010), the velocities of BLR gas are assumed to be predominantly virial in order to use Kepler’s Laws to infer the mass of the central black hole. However, CIV in particular may also be substantially broadened by radiation pressure and quasar outflows (Marconi et al. 2009).

- The “narrow-line region” (NLR), \sim kpc away, from which lower-velocity gas produces correspondingly narrower spectral emission lines, with typical FWHM approximately 500 km/s., and in some cases higher velocities due to thermal or other effects. This FWHM might correspond to typical velocities for gas in the interstellar medium being photoionized by the central black hole. Prominent narrow lines in

the optical include the [OIII] fine structure doublet, a narrow component of H β , and usually [OII].

- A surrounding host galaxy. For quasars, the galactic starlight is typically too faint compared to the quasar to be detected directly, but galactic spectral lines are often present, including both absorption lines and, for many galaxies, a narrow [OII] emission line believed to be associated with star formation. In a typical quasar spectrum, the [OII] emission is likely dominated by photoionization due to a non-thermal continuum as opposed to star formation.

For some individual active galactic nuclei, reverberation mapping (Bentz et al. 2009; Peterson et al. 2004) has been able to confirm the inner portion of this picture, out to the H β broad emission line. In a time series of spectra for the same object, a increase in the continuum luminosity is followed, often hundreds of days later, by a similar flare in CIV and then H β . Assuming the flare propagates outward at the speed of light, the delay can be used to infer a radius to BLR spectral lines.

It should be noted, however, that this simple picture is merely a broad overview of features common to most quasars. Most individual quasars are observed to deviate from this model in any of a wide variety of ways, particularly where high-quality spectra are available and particularly outside of the broad-line region.

There have also been hints that for some quasars, this simple picture might be more clearly wrong. The Boroson & Green (1992) principal component analysis uncovered Eigenvector 1, indicating that for some quasars, changes in specific broad spectral lines are correlated with changes in specific narrow lines. The population of narrow-line Seyfert 1 galaxies contain active nuclei with no traditional broad-line component, but with an intermediate-velocity component up to ~ 2000 km/s. It is unclear whether this intermediate component is a broadened narrow-line region, a weak, high-radius broad-line region, or something else entirely. Similarly, some quasars contain an intermediate H β component (Hu et al. 2008). Even the [OIII] narrow line ($\lambda 4959, 5007$) has been observed to occasionally be broader than 1000 km/s (Marziani et al. 1996; McIntosh et al. 1999).

The [OIII] fine structure doublet is an especially useful indicator for properties of Seyfert galaxies and other low-luminosity active galactic nuclei (AGNs) (Hao et al. 2005). [OIII] is a forbidden line that can only be produced in low-density gas where there are not enough free electrons to allow competing transitions. As such, [OIII] lines are typically found around AGN only in the narrow line region, as interstellar medium gas is lower-density than gas in the broad-line region. Common line-fitting techniques for the nearby H β line rely upon the assumption that the widths of the narrow H β component and [OIII] lines are identical, in order to disentangle the complicated combination of spectral lines surrounding H β . The [OIII] lines, in turn, are typically assumed to be narrow based upon previous studies (Hao et al. 2005). For example, the Shen et al. (2008) virial mass catalog fit the H β broad component along with a narrow component linked to the [OIII] line width and at a maximum FWHM of 1200 km/s.

Although fitting each of these narrow lines as one Gaussian, with a common width, is currently a stan-

dard practice, there is ample evidence that the underlying physics may be more complicated. Forbidden lines at higher ionization potentials do show broader velocity profiles than those with lower ionization potentials (Whittle 1985; De Robertis & Osterbrock 1984), indicating that the narrow-line region may not be monolithic. [OIII], a narrow line heavily studied due because it is typically strong and available in the optical up to $z \sim 0.8$, may be asymmetric with multiple components (Zamanov et al. 2002; Boroson 2005). This might be further evidence of an intermediate-line region, or of outflows (cf. Hall et al. (2002); Ho (2009)).

In this work, we introduce a set of quasars identified via spectral line fitting, characterized by a broadened “narrow” component of H β and often also broadened [OIII] (§ 2). It turns out these “anomalous narrow-line quasars” (ANLs) comprise a distinct population, with a wide variety of properties common to all ANLs but atypical of other quasars. These properties are discussed in § 3, and include many of the characteristics previously reported by Boroson & Green (1992) and Hu et al. (2008), as well as several properties characteristic of narrow-line Seyfert 1s, despite our study focusing on Type I quasars often containing a 10000 km/s broad H β component. In addition, we show that ANL spectra have several additional, previously unreported properties characteristic of this new population. We consider whether these properties might be an artifact of our fitting routines in § 4. Finally, ANLs seem not to fit easily into the standard AGN model, and possible explanations are considered in § 5, as well as issues of nomenclature.

2 ANOMALOUS NARROW-LINE QUASARS

We fit all objects in the Shen et al. (2011) catalog with a prescription similar to Shen et al. (2008), in turn motivated by McLure & Dunlop (2004):

- Using the catalog redshift, we select the spectrum at rest wavelengths [4435, 4700] and [5100, 5535] Å and simultaneously fit the sum of a power-law continuum and an Fe template (Bruhweiler & Verner 2008) convolved with a Gaussian of variable width.

- With the continuum and iron lines removed, the H β line is fit with two Gaussians and the [OIII] doublet with a pair of Gaussians, with the [OIII] doublet is constrained to have the 3:1 amplitude ratio physically required by the fine structure transitions involved and the two [OIII] widths identical to the width of the H β narrow component. Typical uncertainties are 2-15% in both H β velocities, with more luminous quasars and broader components typically best determined.

- The final result is checked for contamination by nearby HeI lines. If HeI contamination is detected, we construct a new line fit with HeI removed. This check is not part of the Shen et al. (2008) fitting prescription.

The Shen et al. (2011) catalog includes best fits for objects with very poor signal to noise and low-amplitude lines. We discard objects with very low H β equivalent width and where a fit containing no H β line had a better χ^2/DOF than a fit containing an H β line. Although the FeII width is often similar to the H β broad component, this is not required in our fitting and for many ANLs, the two have different velocities.

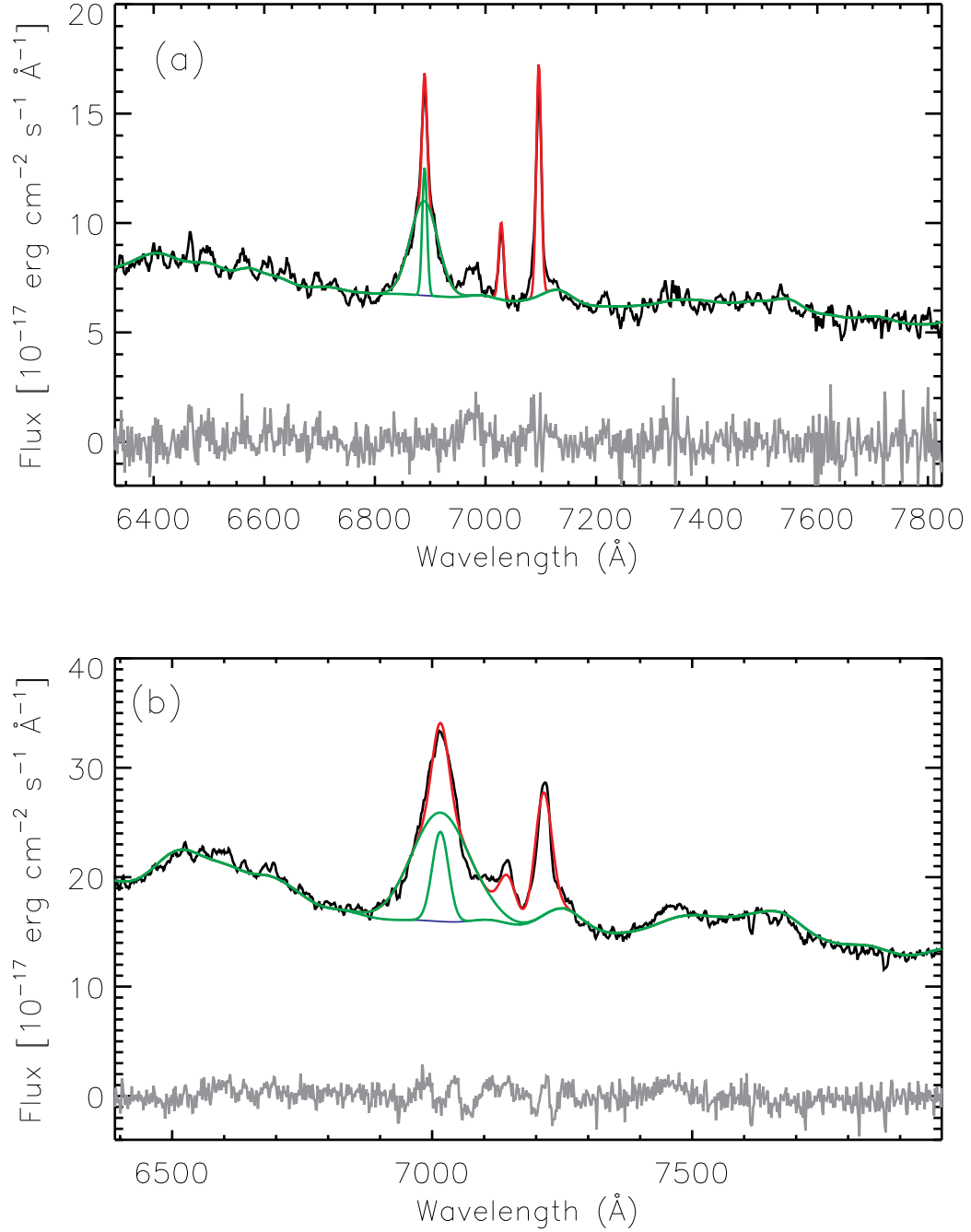


Figure 1. Best-fit sum of continuum and iron (green) and total fit (red) to (a) SDSS J000109.12-004121.6, a ‘standard’ quasar, and (b) SDSS J000011.96+000225.3, an anomalous narrow line quasar. Both H β components are also shown. The residual differences between spectrum (black) and fit are shown in gray.

Because the FeII amplitude is typically far smaller than the stronger of narrow H β and [OIII], alternative templates yield similar results. A sample end result (the first well-measured example sorted by RA) is shown in Fig. 1.

Contrary to previous work, we find a substantial sample of objects with “narrow” H β and [OIII] broader than 1200 km/s using this same technique. In Fig. 1(right), the quasar SDSS J000011.96+000225.3 is shown to exhibit “narrow” lines with a FWHM of 1860 km/s. Further, this is not an isolated example, but rather part of a large class of objects with a broadened H β narrow component. In the Shen et al. (2011) catalog, 30.4% of objects with discernible H β broad lines contain a narrow H β component broader than 1000 km/s.

These anomalous narrow-line quasars can be divided up into two groups based upon their [OIII] lines. For some ANLs, the [OIII] line is suppressed in amplitude, and broadened comparably to the narrow H β component. Several examples of these class of ANLs are exhibited in Fig. 2. For other ANLs, the [OIII] amplitude is suppressed but the line is not equally broadened, as in Fig. 3. For some quasars, it is difficult to clearly determine which of these two groups is a better description, because ANLs often have broad H β lines, low-amplitude [OIII], and enhanced FeII (§ 3), leading to difficulty fitting the [OIII] line well. We estimate that approximately one third of ANLs show broadened H β narrow and broadened [OIII] of a similar width, and the other two thirds show narrower [OIII] than their H β narrow component. In both groups, quasars can be clearly identified as ANLs because H β is a strong, broad line.

We note that although previous SDSS line catalogs (Hao et al. 2005; Shen et al. 2008, 2011) have not reported a substantial sample of ANLs, several similar objects have been found in smaller surveys. Marziani et al. (1996) found an [OIII] λ 5007 FWHM over 1100 km/s for 6 of 52 low-redshift AGN. In a sample of 32 high-luminosity quasars at $2.0 < z < 2.5$, higher redshifts than the ANLs reported in this work, McIntosh et al. (1999) found 12 with [OIII] λ 5007 FWHM ≥ 1200 km/s, and another six between 1000 and 1200 km/s, finding a strong correlation between [OIII] FWHM and quasar luminosity. Forster et al. (2001) point out that the average [OIII] FWHM is 1150 km/s for radio-loud and 1160 km/s for radio-quiet quasars in the McIntosh et al. (1999) sample. Aoki et al. (2005) present an analysis of two quasars with broad [OIII] that is further blue-shifted relative to H β . What we report is that these quasars with broadened [OIII] are part of a distinct and larger class within the SDSS quasar catalog, and that there is also a second, larger part of that class with broadened H β (narrow) accompanied by suppressed but unbroadened [OIII]. As described herein, there are a number of other common properties (both spectral and photometric) for ANLs, as detailed below, that compel us to define a new class of quasars.

3 ANL PROPERTIES

In a typical quasar, the broad-line region is at too high of a density to allow forbidden transitions such as [OIII], implying that these quasars with broader [OIII] (ANLs) might have atypical structure. Thus, the investigation into ANLs begins by determining whether they are atypical in any other

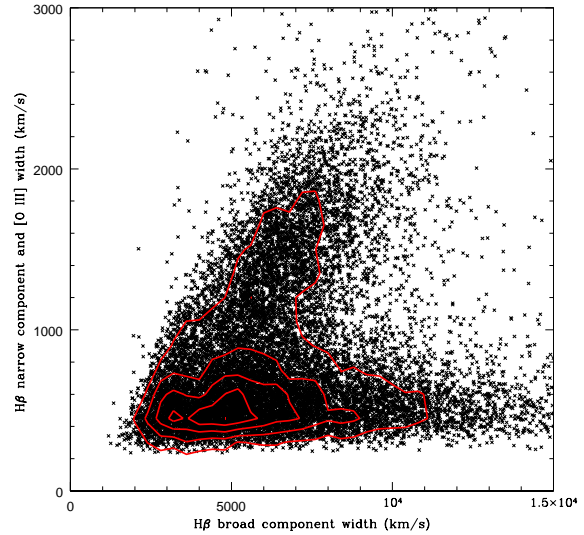


Figure 4. Comparison of the narrow-line FWHM and H β broad-component FWHM for quasars in the SDSS DR7 catalog. Narrower velocities are accompanied by a wide range of H β widths, but ANL narrow-line velocities are well-correlated with broad H β , increasing with increasing broad H β width. Contours are drawn at equally-spaced number densities.

ways, perhaps accompanied by other distinguishing features that might help provide an explanation.

Indeed, a comparison between the broad H β and narrow-line FWHM shows two populations (Fig. 4), one with narrow H β and [OIII] apparently uncorrelated with the H β broad-line width and another with broader [OIII] and narrow H β well correlated with the broad H β component. The Type I quasar sample might thus be composed of two distinct classes of quasars: (1) quasars with standard narrow lines, of the type that has been previously studied and (2) ANL quasars in which the physical process responsible for anomalous narrow lines also results in broader quasar “broad lines”. Because low-density gas is required to allow the forbidden transitions producing the narrow [OIII], the narrow-line region is often assumed to lie far from the central black hole. A very strong outflow reaching the narrow line region could increase the velocity of [OIII] and the narrow component of H β , and would at the same time also increase the velocity of the broad H β component coming from the broad-line region closer to the central black hole.

These two classes may be more difficult to distinguish than previously thought. As indicated in Fig. 4, a cut at ~ 1200 km/s is sufficient to remove standard quasars from an ANL population, but objects with low FWHM of both H β components, classed for our study as standard quasars, might instead lie on a continuation of the ANL branch, or might be a combination of some objects with standard and some objects with ANL physics in their broad-line regions. If so, the true ANL population would comprise more than 30% of the SDSS catalog, and some ANLs would have been well-fit in the Shen et al. (2011) catalog. This possibility is discussed further in § 5.2.

For further investigation, we divide the SDSS DR7 sample into bins by narrow-line width, as in Table 3.

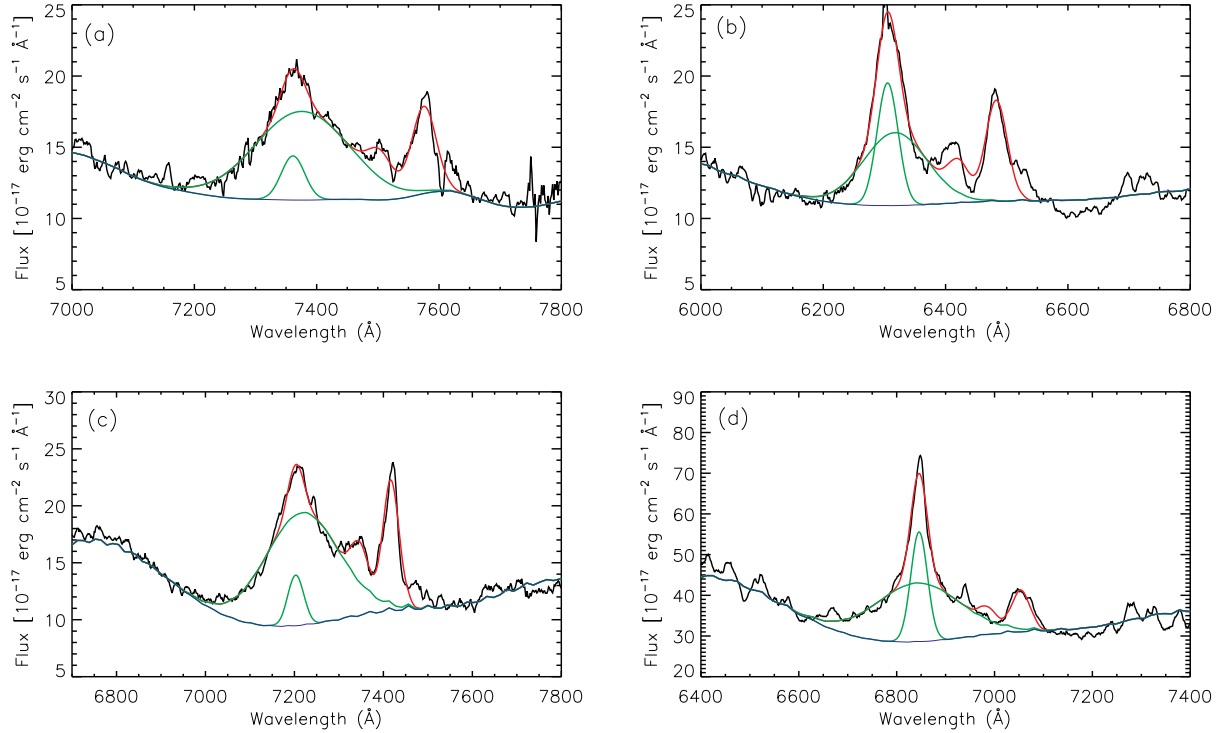


Figure 2. Four examples of anomalous narrow-line quasars exhibiting [OIII] broadening comparable to the narrow H β component. The total fit (red) is composed of a continuum plus FeII fit (blue), two H β components (green), and [OIII]. (a) SDSS J112048.01+631453.9, $z=0.514$; (b) SDSS J145142.83+610747.8, $z=0.296$; (c) SDSS J081528.88+333254.2, $z=0.482$; (d) SDSS J095912.92+445059.0, $z=0.407$

Table 1. Properties of quasars in the SDSS DR7 catalog binned by narrow-line width, including the fraction showing broad absorption in MgII (Shen et al. 2011) and the best-fit FeII amplitude (arbitrary units).

σ (km/s)	FWHM	Color	N	Frac.	‘Best’ N	Frac.	BAL	FeII (arb.)	$\log L_{bol}$
100–200	235–471	Black	3549	0.217	1162	0.217	0.0033	1.59	45.41
200–300	471–706	Black	4941	0.303	1018	0.274	0.0050	2.14	45.51
300–400	706–942	Red	2309	0.141	657	0.123	0.0098	3.25	45.61
400–500	942–1177	Red	1366	0.084	420	0.078	0.0069	4.14	45.68
500–600	1177–1413	Yellow	1086	0.067	394	0.074	0.0084	7.10	45.72
600–700	1413–1648	Green	1018	0.062	432	0.081	0.0065	9.37	45.82
700–800	1648–1884	Cyan	743	0.045	321	0.060	0.0116	10.48	45.90
800–900	1884–2119	Blue	424	0.026	207	0.039	0.0249	11.96	46.00
900–1000	2119–2355	Magenta	227	0.014	110	0.021	0.0284	13.75	46.01

Quasars with standard narrow lines are most common, with the population peaking near the expected 500 km/s line FWHM. However, 30.4% of quasars have narrow-line velocities greater than 1000 km/s, and in nearly one quarter of quasars these velocities are above the Shen et al. (2008) limit of 1200 km/s. Although Fig. 4 indicates that there are two populations of quasars, the quasar fraction decreases monotonically at velocities above the peak. This may indicate that quasars are not necessarily either ANLs or “standard” quasars, but rather can also exist in an intermediate state. Anomalous narrow lines are accompanied, on average,

by an increased luminosity. However, ANLs are also increasingly likely to contain broad absorption lines as measured from MgII in the Shen et al. (2011) catalog.

For a variety of reasons, our best fit may not be a good match for even a well-measured SDSS spectrum, and this is one of the limitations of any automated line-fitting prescription with a small number of free parameters. For well-measured spectra where narrow H β and [OIII] have similar, Gaussian profiles, our fit is generally good. However, many quasars best-fit with narrower “narrow” lines have non-Gaussian profiles, and many anomalous narrow-line quasars

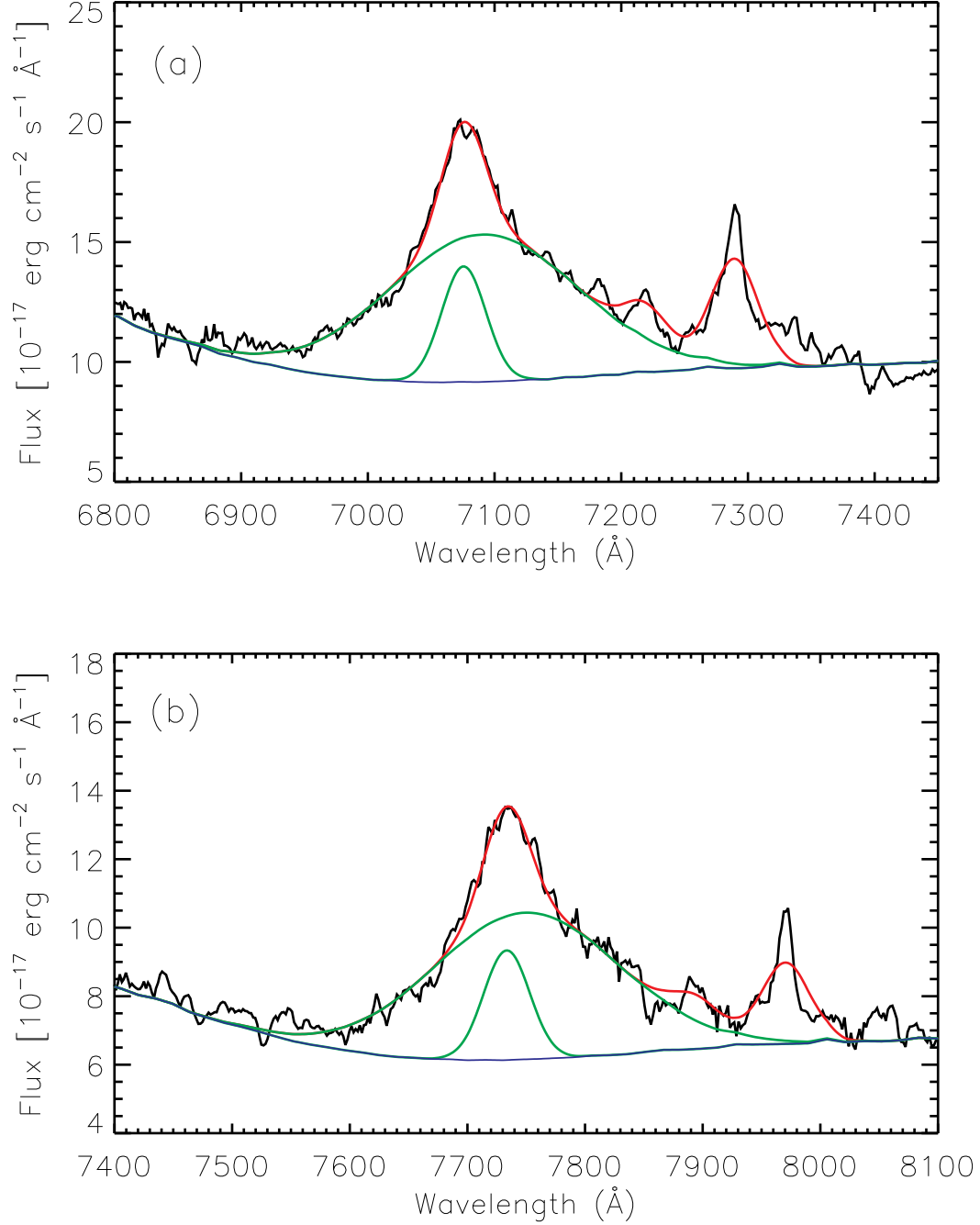


Figure 3. Two examples of anomalous narrow-line quasars exhibiting [OIII] suppression, but without [OIII] broadening comparable to the narrow H β component. The total fit (red) is composed of a continuum plus FeII fit (blue), two H β components (green), and [OIII]. (a) SDSS J170208.34+330700.6, $z=0.658$; (b) SDSS J110103.76+411317.1, $z=0.455$

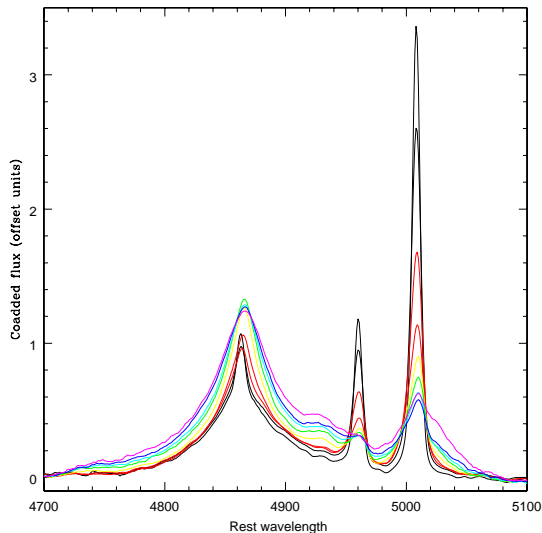


Figure 5. Comparison of co-added quasar spectra around the $H\beta$ and $[OIII]$ lines binned and colored as in Table 3. The continuum and FeII lines have been subtracted.

show a mismatch between the $H\beta$ and $[OIII]$ profiles. In such cases, our fitting routine will typically be dominated by the higher-amplitude of narrow $H\beta$ and $[OIII]$, which typically is $[OIII]$ for lower velocities and $H\beta$ at higher narrow-line velocities (Fig. 5, further described below). Some mismatched ANLs may be objects with a broad blue $[OIII]$ wing component tied to $H\beta$ and in addition to the $OIII$ narrow component, similar to those discussed in Zhang et al. (2011). Quasars with ~ 2000 km/s narrow $H\beta$ and narrower $[OIII]$ are certainly anomalous, but might have a different cause than ANLs with ~ 2000 km/s FWHM for both $H\beta$ and $[OIII]$.

We produce a ‘best’ sample of quasars for which (1) the overall fit χ^2/DOF is good and (2) the χ^2/DOF for the $\sim 50 - 150$ pixels within 2σ of the narrow $H\beta$ and $[OIII]$ is within 0.5 of the total χ^2/DOF . As in Table 3, this sample has a slightly larger ANL fraction than the overall catalog. A very conservative lower bound on the true ANL fraction would be 11%, the fraction of quasars in the entire sample that are ANLs in the ‘best’ sample. A much more likely explanation is that $\sim 11\%$ of quasars are ANLs with both $H\beta$ and $[OIII]$ broadened (Fig. 2), while an additional $\sim 20\%$ of quasars are ANLs with $H\beta$ broadened but $[OIII]$ suppressed and unbroadened (Fig. 3).

Spectra within each bin from Table 3 are co-added to examine the average dependence of spectral lines on $OIII$ width. Each individual spectrum is first smoothed to the resolution of the SDSS spectrograph, then normalized to the monochromatic 5100 Å flux and averaged. Subtracting the best-fit continuum and FeII template results in the spectral lines shown in Fig. 5. As indicated by Fig. 4, varying widths for standard “narrow” lines (black, red) in Fig. 5 are not associated with strong changes in the broad component of $H\beta$. However, broader “narrow” lines are associated with an increase in width of $H\beta$ as well as increasing $H\beta$ line flux. When the $[OIII]$ width increases, it is associated with a de-

clining amplitude, and in total a nearly-constant equivalent width.

Several other spectral features are also responsive to increased narrow-line width (Fig. 6). The continuum tilt increases for ANLs, making them bluer than other quasars. This bluer tilt occurs despite a higher BAL fraction among ANLs (Table 3), which indicates ANLs might be on average dustier than other quasars. Perhaps this continuum slope is explained by ANLs having a higher temperature, also consistent their higher average luminosity. ANLs also show stronger FeII lines (see also Boroson & Green (1992), Table 3). An effort to find ANL indicators available at other redshifts where $[OIII]$ is unavailable finds that $[NeV]$ broadens along with $[OIII]$, while SII does not (Steinhardt & Silverman 2011). The stronger and broader $H\beta$ line might be evidence that the nature of the quasar broad-line region is changing, whether due to a strong outflow or other accretion physics. However, the $MgII$ line (Fig. 6) does not increase in width in ANLs. Since $MgII$ has an ionization potential placing it at a larger radius from the central black hole (Peterson 2008), one possible explanation might be an outflow propagating only partway through the broad-line region.

However, the $[OII] \lambda 3727$ Å line appears sensitive to these changes (Fig. 6). $[OII]$ originates in both narrow-line region gas around the quasar and star formation in the host galaxy (Ho 2005; Kim et al. 2006). If broadened $[OIII]$ is evidence of an outflow broadening the entire narrow-line region, then any $[OII]$ coming from near the quasar would also be broadened. The $[OII]$ amplitude is declining in Fig. 6, but the line width is not increasing.

The decline in $[OII]$ amplitude indicates that the combination of $[OII]$ from all sources, including star formation, diminishes with increasing $[OIII]$ width. One intriguing possibility is that star formation in ANL hosts is quenched by outflows from the central black hole. It is also possible that all quasars inhibit star formation, and that the reduction in $[OII]$ flux between standard Type I and ANL quasars is due to a reduction in the photoionized $[OII]$ in the narrow-line region.

The $[OII]$ centroid appears to shift between different bins in Fig. 6. Although this could be interpreted as a skew in $[OII]$, the redshift is determined primarily by the highest-equivalent width lines. If $H\beta$ is skewed (Fig. 5) in ANLs, the result may be a systematically incorrect redshift, resulting in locating low-amplitude lines such as $[OII]$ at the wrong rest wavelength. A possible indication of this skew is the offset between the broad and narrow components in $H\beta$ fits to ANLs (Figs. 2,3). If the narrow component is blueshifted while the broad component lies at the velocity of the host galaxy, it might induce this sort of skew. This effect may make high-precision redshift determination difficult for ANLs, as their broad emission lines are skewed and their galactic lines are difficult to measure due to their small amplitude.

If this redshift error leading to an $[OII]$ offset is systematic and uniform for fixed narrow-line width, the average decrease in $[OII]$ amplitude will be well-indicated by the co-added spectrum. However, if the offset is non-uniform, high-amplitude lines with different centroids may be co-added to produce a low-amplitude, broader line. Therefore, we fit the $[OII]$ line directly and investigate its properties. As with our $H\beta$ and $[OIII]$ fits, we first fit a combination of continuum and broadened FeII template, then find the best-fit Gaussian for the leftover line profile. We find that the $[OII]$ equivalent width declines by a factor of 2.25 for ANLs compared to standard quasars. The best-fit $[OII]$ width remains typical of a narrow galactic emission line, and the decreased line flux comes from a decrease in $[OII]$ amplitude. For

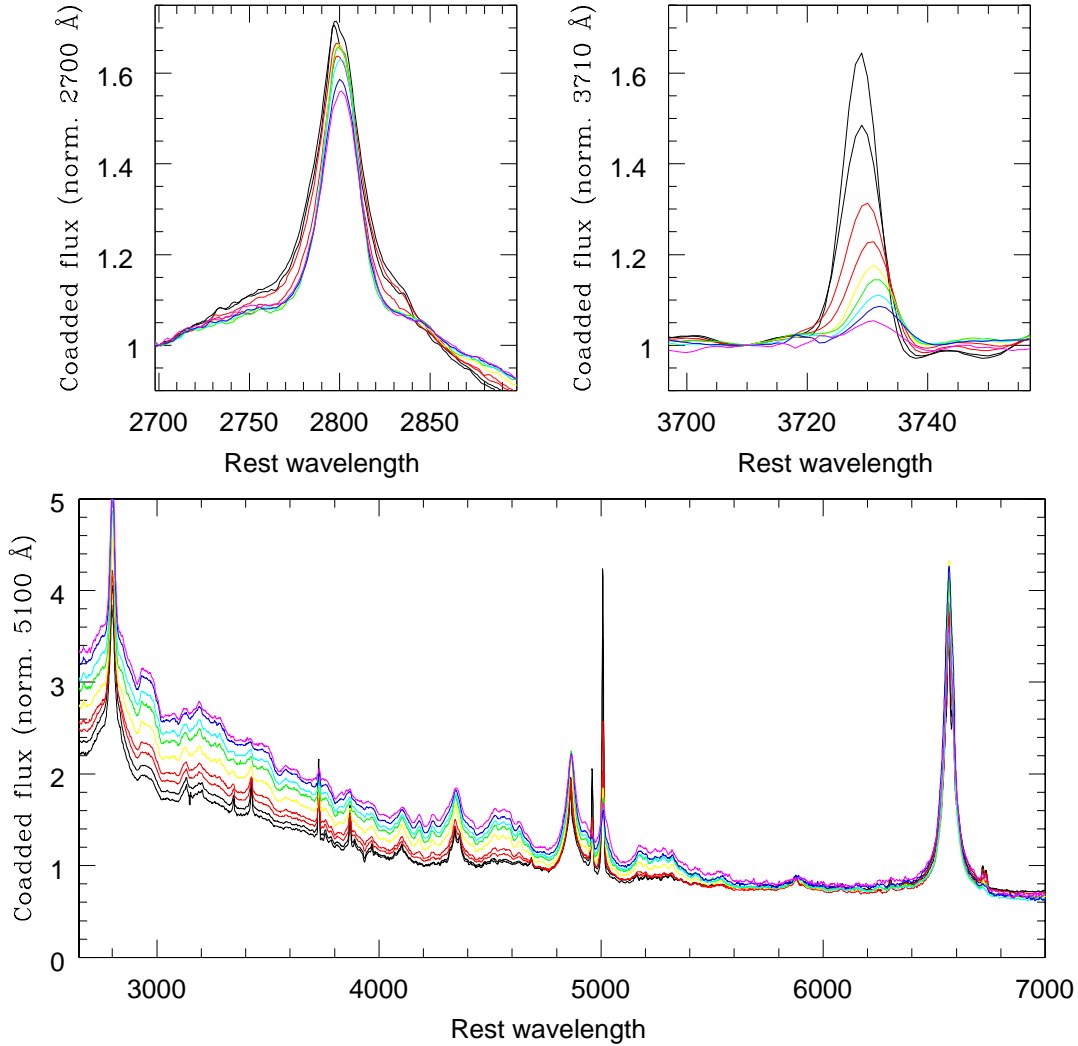


Figure 6. Comparison of co-added quasar spectra at different narrow-line widths binned and colored as in Table 3. For shorter wavelengths, only spectra at sufficiently high redshift were co-added. At top left, the MgII region. At top right, the [OII] region.

low-amplitude [OII], noise is often incorporated into the best-fit line profile, so the true decline may be larger.

4 DEPENDENCE OF ANLS ON FITTING TECHNIQUES

Because of the long history of studying quasar spectra, a report of a large, new spectroscopic class of quasars discovered via spectral line fitting should be met with appropriate skepticism, and it is important to consider whether ANLS might just be an artifact of fitting techniques. Ultimately, the H β -[OIII] complex arises from complicated physics but is fit with a small number of parameters in an automated way, without the underlying model being adjusted individually for tens of thousands of quasars in the SDSS DR7 and future catalogs. As a result, most fits should contain errors. In an effort to more fully disclose some of these errors, we have made a large sample of our fits for ANLS available at <http://member.ipmu.jp/charles.steinhardt/ANL/>. By choos-

ing a technique previously used by McLure & Dunlop (2004) and Shen et al. (2008), we hope to have avoided introducing any novel line-fitting errors. However, we should highlight two specific dangers:

4.1 Continuum Fitting

Errors in continuum fitting could result in incorrectly determining the properties of broad spectral lines, either missing the broad component of H β if too much flux is considered part of the continuum or introducing a false broad component by under-fitting the continuum. Although for $\sim 500 - 1000$ Å windows the continuum is well-fit by a power law, the slope of that power law changes between the MgII and H β region in composite spectra (Vanden Berk et al. 2001), so it must be locally determined. However, most of the pixels near H β are contaminated by either FeII or strong spectral emission lines. Our fitting technique solves this problem by fitting simultaneously for FeII emission and the continuum. An alternative technique would involve

choosing a window free of FeII contamination, such as 5080–5100 Å (Forster et al. 2001), and using these windows to fit the continuum alone. However, in an ANL with broadened [OIII], 5080 Å may not be free of [OIII] contamination, so this window could also provide an erroneous continuum slope.

By simultaneously fitting FeII and continuum, we fit hundreds of SDSS pixels with four parameters, resulting in a well-determined fit. However, although the continuum fits exhibited in Figs. 1-3 appear reasonable, it is difficult to prove that any individual spectrum has been well-fit. Fortunately, it is the broad, rather than the narrow, component of H β that will be strongly affected by errors in continuum fitting. Our report of a large population of ANLs relies on fitting of the narrow component, and thus should not be susceptible to errors in continuum fitting.

4.2 Iron Contamination

Although FeII is a larger problem when fitting MgII rather than H β , there are also FeII lines extending near [OIII]. Further, the strength of iron lines increases strongly in ANLs (Table 3). As with continuum fitting, FeII contamination should not be a problem when determining whether an object is some type of ANL, as the narrow H β component is stronger than FeII and well-measured. However, the combination of strongly suppressed [OIII] and augmented FeII emission is more likely to result in errors fitting [OIII] λ 5007.

The presence of stronger iron lines does make FeII easier to detect and fit. Further, although there are several different FeII templates available, they are typically derived from the spectra of objects with narrower FeII lines, such as 1 Zw 1 (Bruhweiler & Verner 2008). Because these templates are then convolved with a broad Gaussian to simulate FeII with a FWHM of thousands of km/s, differences between templates are minimized, so alternative templates produce a similar ANL sample.

The reduction from the full ANL sample to the ‘best’ sample presented in § 3 uncovered a large population of ANLs in which [OIII] was suppressed but not broadened. Perhaps what we have fit as suppressed and broadened [OIII] in these other cases is instead dominated by strong FeII emission at broad-line region velocities. Because several ANLs show not just a broadened [OIII] λ 5007 line but also equally-broad [OIII] λ 4959, for some objects [OIII] is unambiguously broadened (Fig. 2a,c). In other objects, a combination of HeI contamination and highly-suppressed [OIII] λ 4959 might make an alternative explanation involving FeII more plausible (Fig. 2,d).

The FeII FWHM is often linked to the broad H β component FWHM. However, in ANLs with broadened [OIII], the [OIII] FWHM is instead linked to the H β narrow component, an apparent mismatch. However, ANL broad-line regions appear to behave anomalously in several ways compared to BLRs in standard quasars, so perhaps iron emission is also different. Iron contamination is therefore a plausible concern when fitting [OIII] for some ANLs, but cannot be responsible for miscategorizing objects as ANLs based upon the H β narrow component.

4.3 Modeling H β With Two Gaussians

In this work, we choose to model the H β line as a pair of Gaussians, and each of the two [OIII] lines as one Gaussian. This is in keeping with standard practice for large catalogs (cf. Shen et al. (2011, 2008); McLure & Dunlop (2004); Rafiee & Hall (2010), etc.). Even some past work using more complicated fitting prescriptions reported their results using two Gaussians (Hu et al. 2008). As such, if the correct interpretation of this result turns out to be merely that the two-Gaussian fit is faulty for $\sim 30\%$ of quasars, it would still be important to understand and correct for this problem, and that correction would change the results of

existing statistical studies of the SDSS quasar population using H β line fitting, including virial mass catalogs.

However, the question remains as to whether two Gaussian components is a good representation of the H β line, particularly for ANLs. When only one component of an ANL is allowed to be broader than 1200 km/s, effectively the entire line shape is modeled as one Gaussian, where the fitting in this work uses two. Fitting two broad Gaussians to a line shape closer to one Gaussian, but not exactly Gaussian, might lead to fit composed of the dominant Gaussian and a second, correlated Gaussian that would be artificial and representative of line non-Gaussianity. So, is one Gaussian actually a better fit for ANLs? For that matter, is a third Gaussian an even better fit, as reported by Hu et al. (2008)?

The simplest measure of whether two Gaussians provide a better fit is to examine the χ^2/DOF for each fit. We consider the part of the spectrum within 2σ of the peak, as defined by the broadest component. For all quasars, the χ^2/DOF averages 1.31 for two-Gaussian fits and 1.70 for one-Gaussian fits. For ANLs, two-Gaussian fits average 1.30 while one-Gaussian fits average 2.02. Adding a third Gaussian, however, provides no such substantial help; a three Gaussian fit reduces the χ^2/DOF from 1.31 to 1.29 for all quasars and, like the two-Gaussian fit, averages 1.30 for ANLs. Thus, it is clear that the second-strongest component of the H β lineshape is strong, while the third-largest is much weaker. A two-Gaussian fit therefore seems reasonable, although the correct line shape may not contain Gaussians at all; a correct fit should produce a χ^2/DOF of 1. However, errors in SDSS are likely correlated between neighboring pixels (McDonald et al. 2006), so the reported uncertainties used in producing these values for χ^2 may not be trustworthy. This χ^2 analysis is a good sanity check on our fitting technique, but is certainly not proof that the lines are being fit well.

Ultimately, fitting lines is an art, there are many complex prescriptions that can be used to produce higher-quality fits for individual spectra, and it is unrealistic to tailor individual fits for 100,000 spectra in SDSS, or even more in future surveys. We believe the best we can do as scientists is to use public data, make a collection our fits public rather than only exhibit our best examples (a collection is available at <http://member.ipmu.jp/charles.steinhardt/ANL/>), and encourage other experts to use alternative prescriptions for H β . It appears very difficult to fit ANLs well with one broad component and one component under 1200 km/s in FWHM.

In general, there are many errors arising from fitting the spectrum of a complex object with a simplistic model containing little physics and a small number of parameters. These errors will likely result in some incorrect fits, it would be difficult to believe reported H β narrow widths to within 1%. However, many ANLs have narrow H β measured at over 2000 km/s, and even a rudimentary fit “by eye” of the narrow H β lines displayed in Figs. 1-3 cannot accommodate typical narrow H β velocities of under 1000 km/s. These details of line-fitting are important when, for example, using precision line measurements to produce a quasar virial mass. However, they cannot be responsible for overestimating the narrow H β width by such a large factor in 30% of the SDSS quasar catalog.

5 DISCUSSION

We report a new class of Type I quasars with broadened narrow H β and [OIII]. These quasars (ANLs) include over 1/4 of all ~ 16000 SDSS quasars for which H β is well-measured ($z < 0.8$). However, previous line-fitting catalogs of SDSS quasars have not reported finding a large population of ANLs, likely because selection and fitting routines assume that [OIII] is a narrow line. The existence of these objects now necessitates a re-examination

of other selection criteria in SDSS and similar surveys. In particular, the presence of a strong, narrow [OIII] line is often a strong component of Type II quasar and Seyfert galaxy selection, since broader lines may not be present. Any type II ANLs or ANL Seyferts would likely be selected against during the production of such catalogs.

Several previous examples have been reported of other AGNs with anomalous narrow lines. These include Seyferts with broadened or skewed [OIII] (cf. Xu & Komossa (2011)), as well as quasars with multiple broad H β components (Hu et al. 2008), with the broader broad component redshifted with regard to the narrower one (Sulentic et al. 2002; Collin et al. 2006).

ANLs, however, not only show two well-centered broad components but represent approximately one quarter of the SDSS quasar catalog at $z < 0.8$, with thousands of examples. As such their origin is a compelling puzzle. The spectra of these quasars provide enough evidence to analyze several possible explanations: **Could ANLs be created by an outflow into the narrow-line region?** Given that outflows are a common property of most quasars (Elvis 2000), it would not be surprising to find that a large population exists with discernable evidence for possible non-virial gas motion in the broad-line (and narrow-line) region. Although there is a slight skew to [OIII] and the narrow component of H β in co-added ANL spectra (Fig. 5), the lines are mostly symmetric. Thus, any outflow must be similarly symmetrical, meaning that light from both sides of the outflow is visible. Otherwise, these lines would be more strongly skewed, just as strong asymmetric outflows can skew CIV emission (Shen et al. 2008).

Moreover, MgII, which emanates from the outer portion of the broad-line region, does not increase in width in ANLs (Fig. 6). The narrow-line region, containing [OIII], lies further from the central black hole than the broad-line region. Thus, since any outflow does not reach past the edge of the broad-line region, ANLs are not created by an outflow into the narrow-line region. The broad component of H β also comes from the broad-line region, but its ionization potential places it closer to the central black hole than MgII. Therefore, an outflow that does not reach MgII-emitting gas could still be responsible for higher velocities in gas producing the broad component of H β . An alternative option might be an outflow, larger than the accretion disk, that is able to emit H β (and, presumably, CIV), but unable to emit MgII.

Could ANLs be created by [OIII] emission in the broad-line region? As a forbidden line, [OIII] requires a low density. In a typical Type I quasar, the broad-line region is too dense to allow [OIII] emission, which is why [OIII] does not have a prominent broad-line component. In ANLs, the line flux from H β and MgII, both emitted in the broad-line region is comparable to or larger than other Type I quasars. So, the broad-line region density is unlikely to be substantially lower. Further, if [OIII] and the narrow component of H β are in the broad-line region, where is the broad component of H β located?

One way to test this picture is to consider the evidence from virial mass estimates. As described in (Steinhardt & Silverman 2011), the H β broad component yields a systematically larger mass estimate than MgII for ANLs. Unlike H β , MgII is not strongly correlated with changes in [OIII] for ANLs, and therefore MgII is likely the better mass indicator. For agreement, the H β broad component must be placed at less than half of the radius inferred from the continuum luminosity - broad line region radius relation calibrated by reverberation mapping. If the H β narrow component and [OIII] were instead placed at that radius, it would result in virial masses 1-2 dex below those produced using MgII. Thus, [OIII] emission from virialized broad-line region gas does not seem to fit the available evidence, although some of that evidence may not be reliable.

Could ANLs be typical Type I quasars viewed only from certain angles where an outflow is seen most clearly? [OII] emission comes in part from star formation and in part from

larger radii than [OIII], the latter due to its lower ionization state. Thus, [OII] emission sharply declining (Fig. 6) with broadened [OIII] seems to indicate that ANLs lie in host galaxies, or at least \sim kpc scale central regions, with different properties than other Type I quasars. This would not happen merely due to geometry. Indeed, it is a puzzle that the [OII] line indicates a connection between the host galaxy and the quasar, while the unchanging MgII indicates that the connection is not directly due to a direct outflow.

Could ANLs be a pre-turnoff phase of the quasar duty cycle? The decreased [OII] equivalent width, coming from a combination of star formation and narrow-line region gas, might indicate a reduced supply of gas and dust to the central black hole, perhaps further reduced by a strong outflow. This, in turn, could cause the central quasar to go quiescent, with ANLs an intermediate phase as the quasar turns off. However, the average luminosity of ANLs is actually higher than other quasars (Table 3). An upcoming luminosity decrease would not necessarily render the quasar quiescent, and the response time to a reduced inflow \sim kpc away is long. Nearby, ANLs might actually have more dust available than average Type I quasars, as they are more likely to contain broad absorption lines (Table 3). This picture also does not yet explain the broadened H β and [OIII] lines.

So, although several scenarios present themselves, none yet seems able to fit all of the available evidence.

5.1 ANLs and Feedback

There is known to be a link between the properties of lower-luminosity active galactic nuclei and their hosts (Kauffmann et al. 2003; Silverman et al. 2009; Schawinski et al. 2010; Cardamone et al. 2010). Although co-evolution of the quasar and its host galaxy has long been expected and even assumed, direct evidence for this idea has not yet been forthcoming, primarily because the quasar dominates its host and because the peak quasar number density lies at $z \sim 2$, where resolving the host galaxy as separate from the quasar cannot be done with current ground-based instruments and where the quasar itself, the accretion disk and the broad-line region cannot be resolved with any existing instruments.

One particularly striking feature of ANL quasars is the strong link in co-added ANL spectra (Fig. 6) between [OIII], produced either in nearby heated interstellar medium or closer to the central black hole, and [OII], produced in photoionization \sim kpc from the black hole and in star formation in the host galaxy. The correlation between ANLs and their hosts appears to be evidence of some sort of feedback or linked evolution. Further work, including a physical model for that link, is needed to understand whether we are seeing feedback, co-evolution, perhaps some other process that, as a byproduct, both quenches star formation and broadens the [OIII] line.

5.2 Nomenclature

One of the difficulties in reporting anomalous narrow-line quasars has come in choosing the terminology. In many ways, a better description might invoke an unsatisfying combination such as “broad narrow-line”, or even “broad narrow H β ”, in describing these quasars. Alternatively, perhaps they might be named in analogy with Seyfert nomenclature (e.g., NLSy1). It was even pointed out to the authors that with ANLs comprising as much as 30% of the quasar catalog, their narrow lines aren’t really anomalous. The root problem is that a set of lines conventionally referred to as “narrow” are often found at velocities typically termed “broad”, and it may be difficult to satisfactorily describe these objects without altering common terminology. It is our hope that future work will produce a physical understanding of ANLs

and allow a name representative of their origin rather than their spectra.

It should also be noted that the selection of ANLs in this study has been based entirely upon spectroscopic criteria, i.e., their $H\beta$ narrow component is anomalously broad. A more natural categorization might be based upon the physics of their broad-line regions. For example, quasars might be classed as either virial (VQ) or non-virial (NVQ) based upon their broad-line regions. As discussed in followup work, many ANLs appear to have non-virial broad-line regions (Steinhardt & Silverman 2011). One might guess that quasars on the diagonal branch of Fig. 4 might be NVQs, while quasars on the horizontal branch are VQs, with the quasars in the lower-left intersection of the two branches perhaps consisting of a mixture of both VQs and NVQs. In this interpretation, what we have currently labeled our ANL sample would consist most of NVQs with a few VQs mixed in, while our “standard” quasar sample would consist mostly of VQs but with a substantial number of NVQs as well at lower-left.

This work has defined ANLs as a population for which standard assumptions about the broad- and narrow-line regions appear to be false. This is a useful definition because line-fitting catalogs are often predicated upon these assumptions, and for ANLs an amended technique must be used. The best definition would simultaneously divide quasars spectroscopically and physically. However, if additional spectral properties cannot break the degeneracy in the lower-left of Fig. 4, it may even be possible that multiple categorizations are required.

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